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NUMERICAL SIMULATION OF HYDRODYNAMIC RAM

Kent D. Kimsey

February 1980

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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The EPIC-2 code has been used for the simulation of a kinetic energy projectile, with an L/D (length to diameter) ratio of 3, impacting at normal obliquity a cylindrical fuel cell simulator. A discussion of the predicted hydrodynamic ram event is presented along with a comparison with experimental data.

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I. INTRODUCTION

Hydrodynamic ram refers to the high pressures that are developed in a fluid when a fluid reservoir is penetrated by a K.E. (kinetic energy) projectile. Hydrodynamic ram in aircraft fuel cells can damage structural components or rupture tank walls which in turn can lead to fuel starvation, fire and explosion. Hydrodynamic ram is a paramount threat to today's combat aircraft.

The hydrodynamic ram event is generally considered to consist of a shock phase, a drag phase, a cavitation phase and an exit phase. The shock phase occurs during initial impact with the fluid at which time the projectile impulsively accelerates the fluid and generates an intense pressure field bounded by a hemispherical shock wave. This shock wave expands radially away from the impact point and may produce petaling of the entrance panel. As the projectile traverses the fluid it transfers a portion of its momentum to the fluid as it is decelerated due to viscous drag. If the projectile tumbles in the fluid, a significantly larger portion of the projectile's momentum will be transferred to the fluid. The radial velocities imparted to the fluid during the drag phase lead to the formation of a cavity behind the penetrator. This is often termed the cavitation phase. As the fluid seeks to regain its undisturbed condition, the cavity will oscillate. The time interval during which the exit panel of the fluid cell is perforated by the K.E. projectile is referred to as the exit phase. All of the above phases of hydrodynamic ram have been observed experimentally[1-3]. The collection of papers presented in Reference 4 provides a portrait of the state-of-the-art of analytical and empirical approaches to understanding the hydrodynamic ram phenomenon.

This report presents the results of a numerical simulation of a K.E. projectile with an L/D (length to diameter) ratio of 3 impacting at normal obliquity a cylindrical fuel cell simulator. Section II presents a description of the numerical model and Section III provides a discussion of the results and comparison with available experimental data.

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[1]*Ball, R. E., "Structural Response of Fluid-Containing-Tanks to Penetrating Projectiles (Hydraulic Ram) - A Comparison of Experimental and Analytical Results", Naval Postgraduate School, Monterey, California, NPS-57Bp76051, May 1976.*

[2]*Stepka, F.S. and Morse, C.R., "Preliminary Investigation of Catastrophic Fracture of Liquid-filled Tanks Impacted by High-Velocity Particles", NASA TN D1537, May 1963.*

[3]*Stepka, F.S., Morse, C.R., and Dengler, R.P., "Investigation of Characteristics of Pressure Waves Generated in Water Filled Tanks Impacted by High-Velocity Projectiles", NASA TN D1343, December 1965.*

[4]*Hydrodynamic Ram Seminar, University of Dayton, Dayton Ohio, May 1977, Technical Report AFFDL-TR-77-32.*

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II. NUMERICAL MODEL

Dynamic analysis of a K.E. projectile penetrating a fluid-filled cylinder has been performed using the two-dimensional EPIC-2 code[5]. The hydrodynamic ram event simulated consists of an S7 steel penetrator with an L/D of 3 striking a cylindrical fuel cell simulator. The fuel cell walls are composed of 1.8mm of 2024-T3 Al with a tank depth of 15.24cm and an outside diameter of 50.8cm. The 50 gram, hemispherically capped projectile impacts the aluminum entrance panel with a striking velocity, V_s, of 914 m/s.

Initially the projectile was modeled as a deformable continuum. After perforating the entrance panel negligible deformation of the projectile could be detected. At later times, approximately 35 μs, in the penetration process the projectile exhibited unrealistic distortions due to the finite elements adjacent to the penetrator "locking-up". This "locking-up" results from the artificially high hydrostatic pressure which is generated in elements that are severly distorted when the Mie-Gruneisen equation of state is used to predict hydrostatic pressures. This "locking-up" of water elements tends to transform the hemispherical cap into a conical cap at late times. Therefore, it was felt that a better numerical simulation would be obtained by modeling the penetrator as a nondeformable continuum.

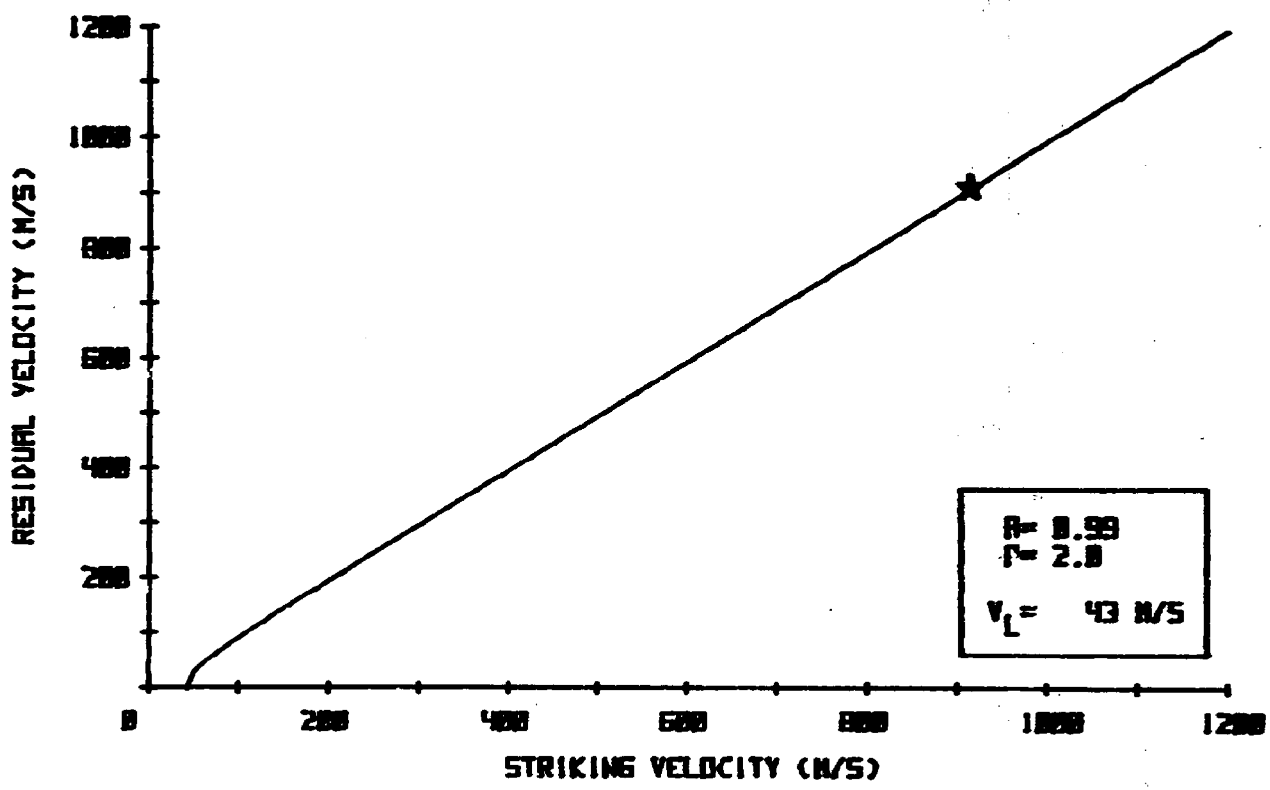
The aluminum entrance panel offers negligible resistance to the steel penetrator which is modeled as a rigid body. The V_s-V_r curve, which has been obtained using Lambert's equation[6], shown in Figure 1 shows this to be an overmatch situation insofar as the fuel cell walls are concerned. Perforation of the entrance panel reduces the penetrator's velocity by less than one percent giving a residual velocity, V_r, of 909 m/s. In light of this "over-kill" condition a plug with a diameter slightly larger than one projectile diameter has been removed from the entrance panel, and the simulation has been initiated with the nose of the penetrator tangent to the fluid surface. The initial configuration of this hydrodynamic ram simulation is shown schematically in Figure 2.

EPIC-2 uses constant strain triangles to discretize a continuum and the hydrostatic pressure in a given element is computed using the Mie-Gruneisen equation of state. For this particular application of the EPIC-2 code the finite element model consists of 5424 elements and 2943 nodes. The fluid is simulated as water and sliding is permitted between the projectile and the water as well as between the water and the "wet" side of the entrance and exit panels.

---

[5] *Johnson, G.R., "EPIC-2 A Computer Program For Elastic Plastic Impact Computations in 2 Dimensions Plus Spin", Honeywell Inc., Defense System Division, Contract Report ARBRL-CR-00373, June 1978.* (AD #A058786)

[6] *Lambert, J.P., "A Residual Velocity Predictive Model for Long Rod Penetrators, Ballistic Research Laboratory Report ARBRL-MR-02828, April 1978.* (AD #B027660L)



NORMAL INCIDENCE

Figure 1. V_s-V_r curve for steel penetrator vs 2024-T3 aluminum

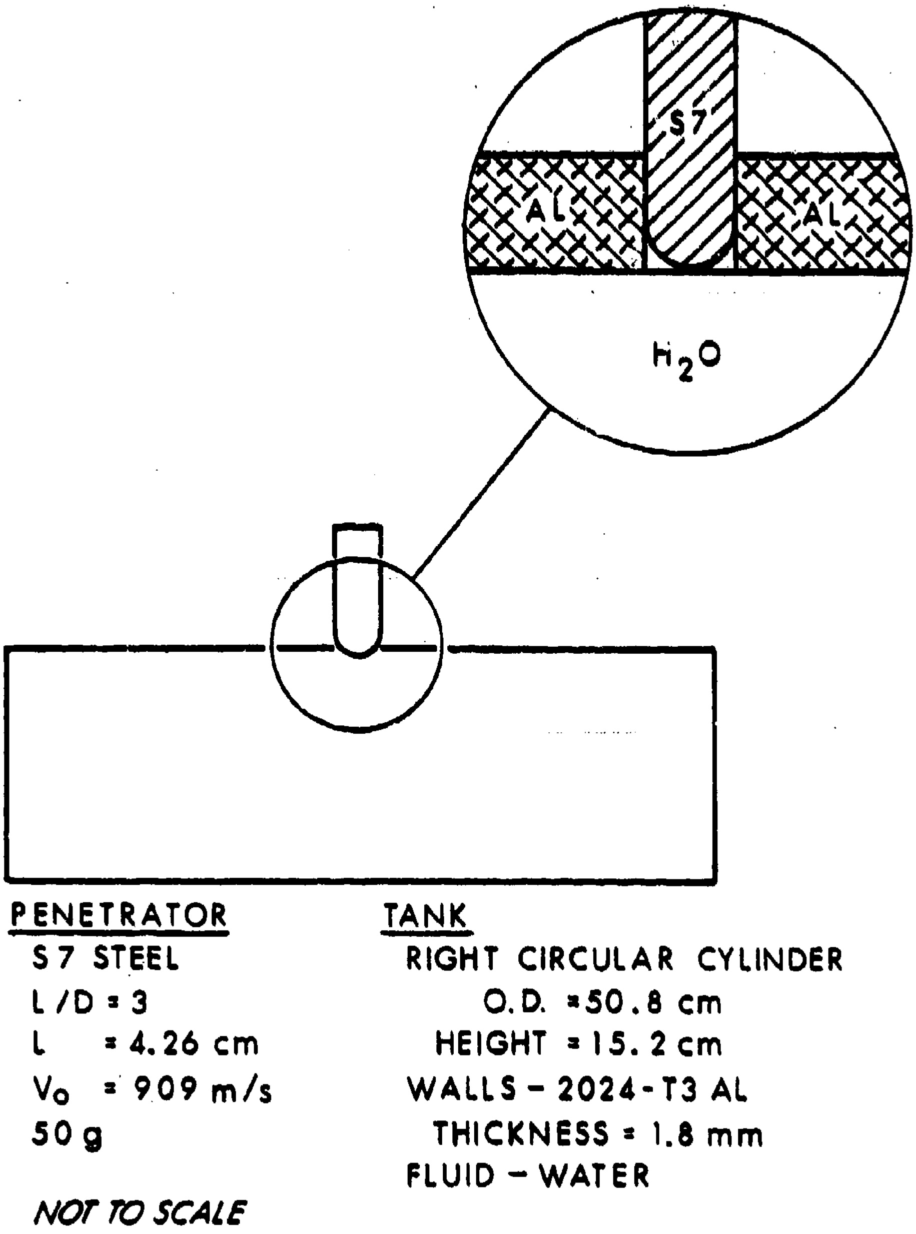


Figure 2. Initial conditions of hydrodynamic ram simulation

The sliding surface technique incorporated in the Lagrangian formulation of EPIC-2 evolves around the designation of master and slave nodes. The technique has the effect of assuming a frictionless surface. In the event a slave node penetrates a master surface element, during a given integration time increment, it is repositioned onto the master surface by conserving translational and rotational momenta and matching the slave node normal velocity with the normal velocity of the master surface at the location of the slave node[5]. For the hydrodynamic ram simulation the projectile has been designated the master surface and a column of water with a radius of 1.3 projectile radii running the entire tank depth, has been designated as slave nodes. Designation of the interior nodes of the water elements to be slave nodes permits the water elements to be completely failed (i.e. the element produces no stresses or pressures) upon exceeding an equivalent strain of 2.5, and permits the simulation of the eroding process or cavity formation of the hydrodynamic ram phenomenon.

III. RESULTS AND CONCLUSIONS

All phases except the exit phase of the hydrodynamic ram event have been simulated with the EPIC-2 code. Figures 3 - 7 present a collage of pressure contour maps in the water. It should be noted that the analysis is an axisymmetric solution and the projectile is restrained from tumbling. Tumbling frequently occurs in experiments with small L/D ratios unless drag flares or other means of stabilization are provided.

The formation of a hemispherical shock wave is clearly delineated in Figure 3. This snap shot of the shock phase shows that slight petaling of the entrance panel has occured as a result of the impulsive acceleration imparted to the entrance panel which has been observed in velocity vector maps, see Appendix A. The impulsive acceleration of the fluid during the shock phase generates peak pressures which are much higher (an order of magnitude) than those observed during the drag phase, see Figures 4 - 7. The duration of the pressure pulses generated during the drag phase is considerably longer than that observed during the shock phase.

The simulation has been terminated at 180 μs at which time the exit panel has been sufficiently loaded to initiate bulging prior to perforation by the projectile. The entrance panel has been deflected considerably and an additional cavity between the entrance panel and the water has formed (Figure 7). The radial velocity imparted to the water (see velocity vector maps Appendix A) as the projectile penetrates the water leads to the formation of a cavity behind the projectile. The development of this cavity is portrayed in the computational grid maps in Appendix B. This cavity appears narrower than those which have been reported in the literature. However, quite frequently in experiments the projectile tumbles in the fluid thereby transferring more momentum to the fluid which generates a larger cavity than would be generated if the projectile did not tumble. Thus, for the axisymmetric solution presented here a narrow cavity prediction was anticipated.

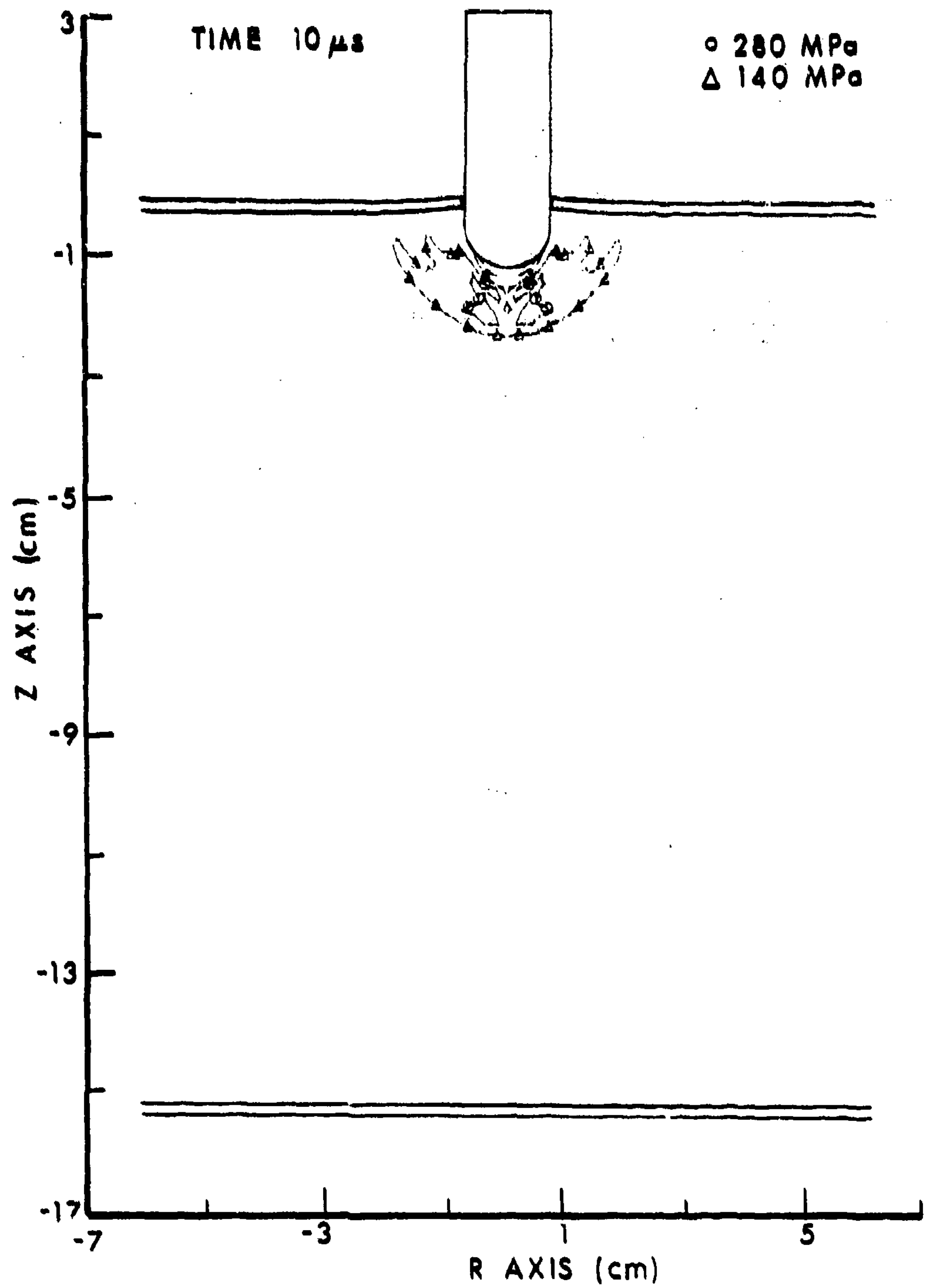


Figure 3. Pressure contour map, t=10 μs

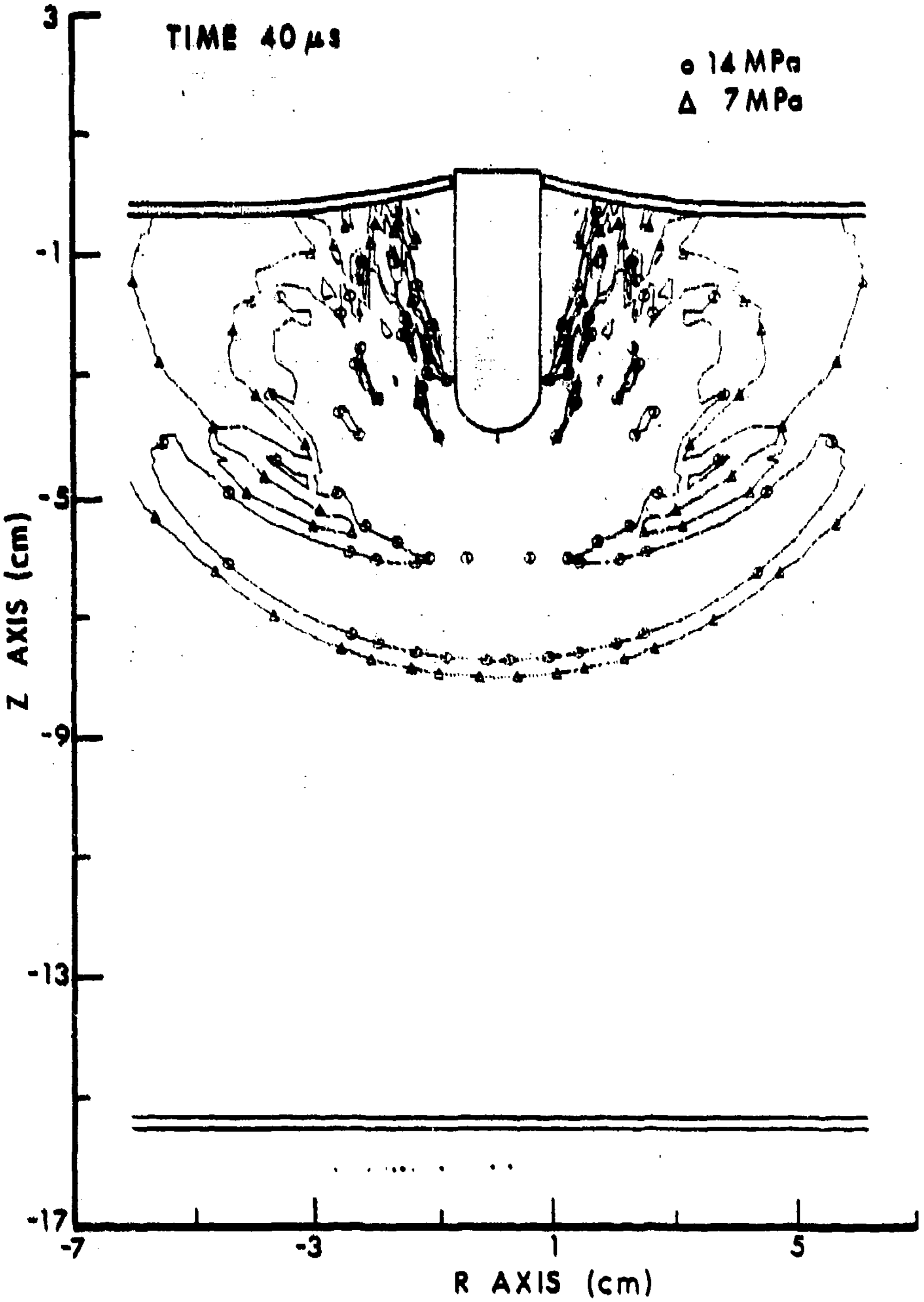


Figure 4. Pressure contour map, t=40 μs

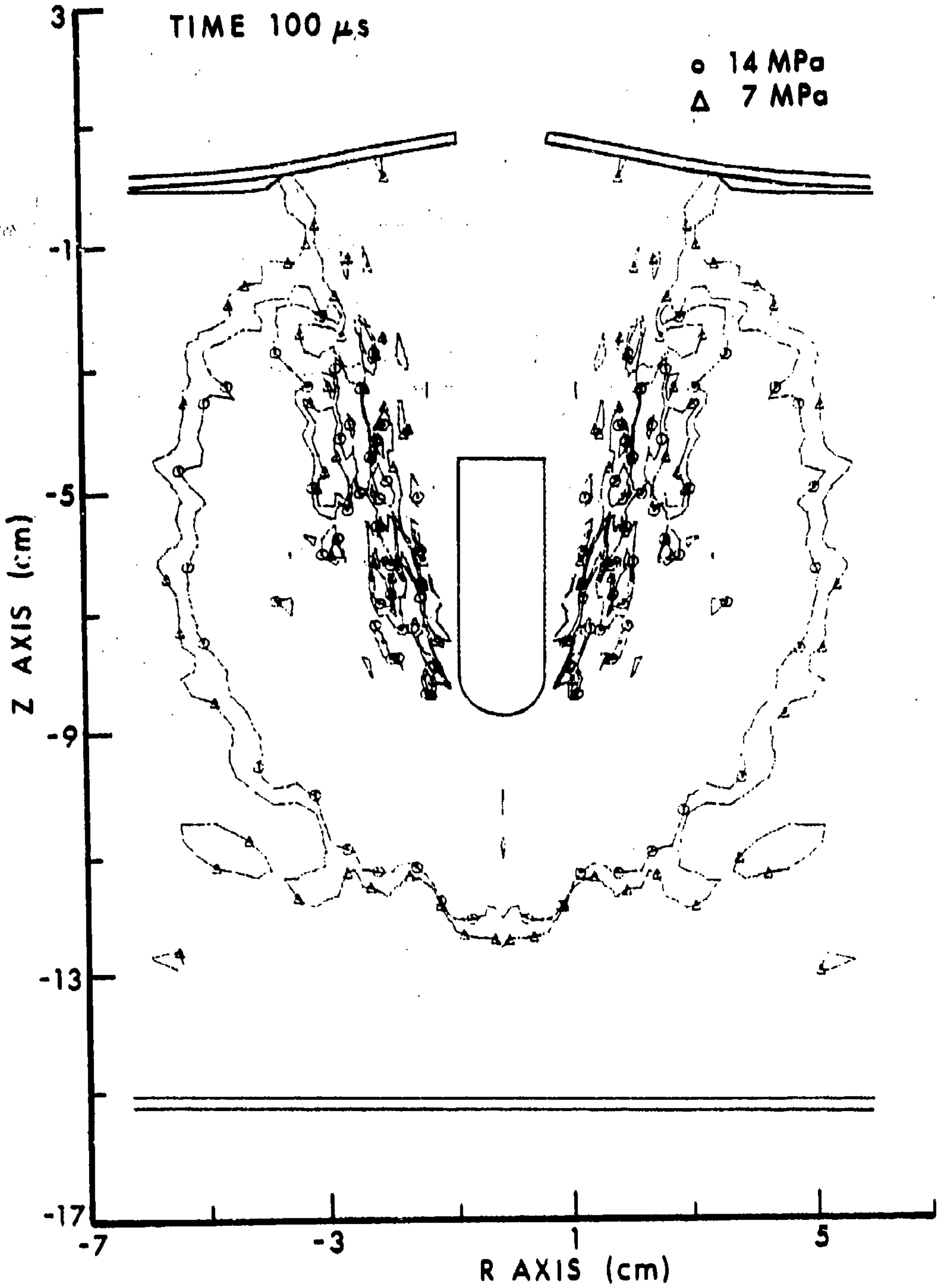


Figure 5. Pressure contour map, t=100 μs

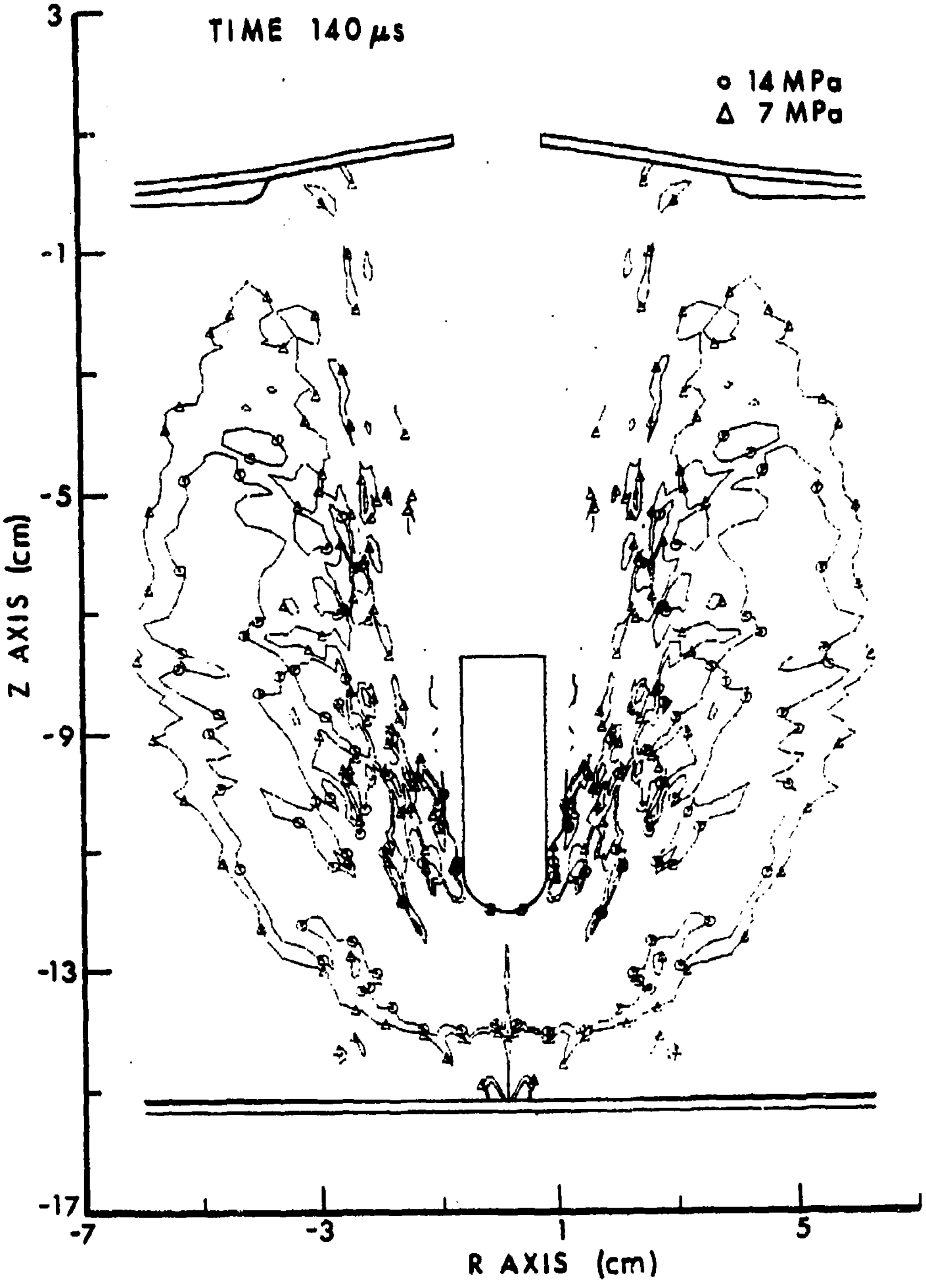


Figure 6. Pressure contour map, t=140 μs

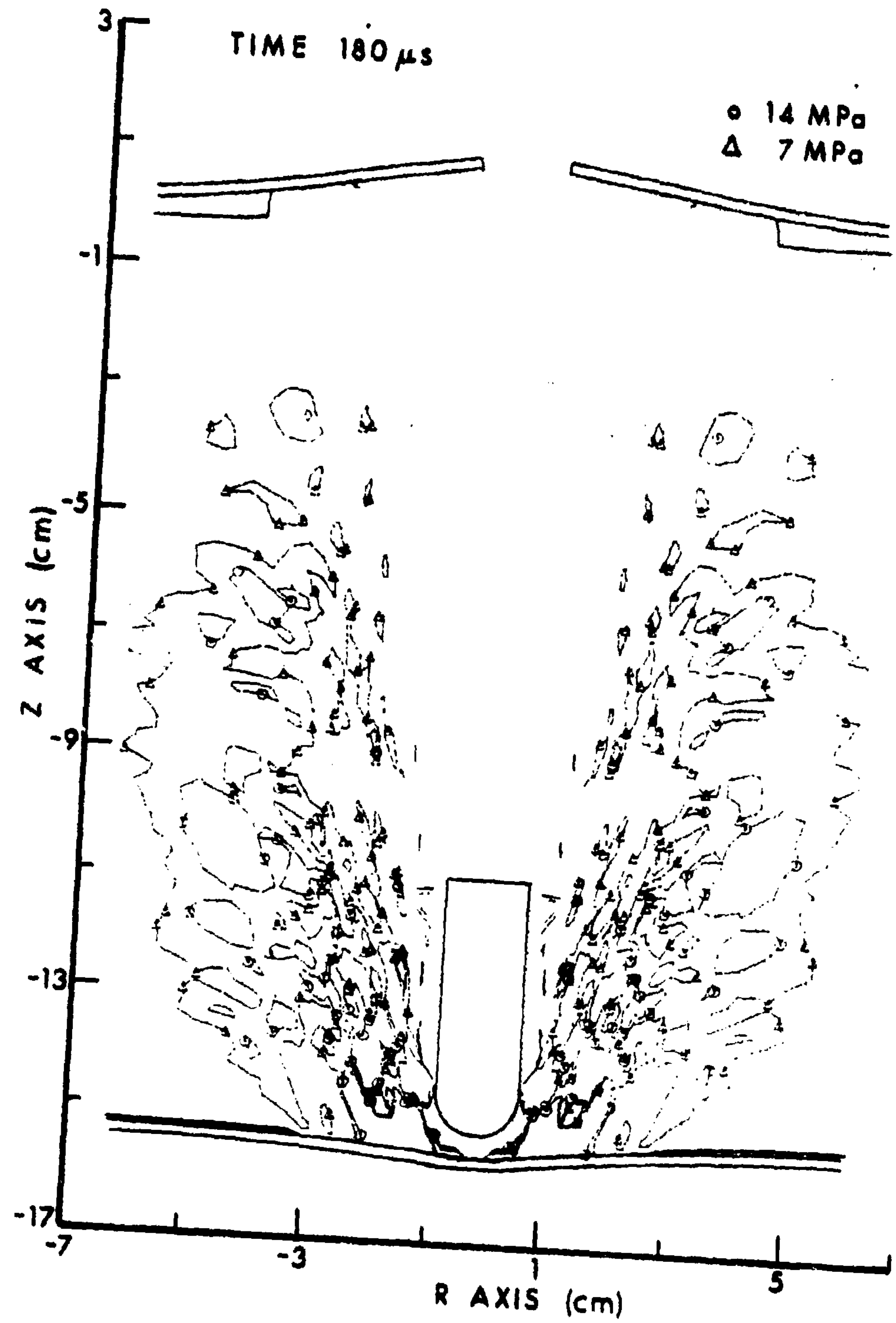


Figure 7. Pressure contour map, t=180 μs

The computational grid maps presented in Appendix B display those elements which have an equivalent strain less than 2.5. Elements which have undergone an equivalent strain greater than 2.5 are severely distorted and realistically would play no role in determining projectile response. These elements have therefore been eliminated or failed. Failure of an element implies that the element definition is destroyed, although the nodes and their associated mass and velocity are retained to conserve mass, energy, and momentum. Furthermore, those elements which have an "F" inside them identify those elements that have exceeded an equivalent strain of 0.02.

Reference 7 presents the following equation relating the striking and residual velocity of a projectile penetrating a water-filled container without tumbling:

$$\frac{V_r}{V_s} = e^{-\frac{C_D \rho_w t}{2 \rho_p L \cdot \cos \theta}} \qquad (1)$$

where:

V_r - Residual velocity of the penetrator

V_s - Striking velocity of the penetrator

C_D - Drag coefficient of the penetrator

ρ_w - Density of the water

ρ_p - Density of the penetrator material

t - Effective separation distance of the entrance and exit panels of the tank

θ - Obliquity angle

L - Penetrator length.

Equation (1) is used therein to compute residual velocities for a series of L/D of 5 projectiles penetrating 15.24cm of water. Striking velocities were reported to range from 0.9 km/s to 3 km/s and for tests at zero degrees obliquity, no appreciable change in angle of attack at the exit panel was observed. Generally, the calculated residual velocity was somewhat higher than the measured values, a discrepancy attributed to the projectile pitching slightly in the tank thereby increasing its drag coefficient.

[7] *"Terminal Ballistics of Rod Penetrators," AVCO Systems Division, AVSD-0201-78-RR.*

The drag coefficient for the L/D of 3, hemispherically capped projectile discussed in this report is estimated to be between 0.7 and 0.8[8]. These drag coefficients predict a 15% and a 17% reduction in projectile velocity respectively. At 180 μs, see Figure 7, the projectile is near the exit panel and EPIC-2 predicts a 13.6% reduction in projectile velocity or a residual velocity of approximately 776 m/s. The projectile's velocity will be further reduced in penetrating the remaining fluid and the exit panel. The velocity decay predicted using EPIC-2 appears to be in line with that which has been measured in experiments with projectiles of similar design.

The use of EPIC-2 in understanding the hydrodynamic ram phenomenon looks promising. In this analysis EPIC-2 has confirmed that the entrance panel petaling results from the water impulsively accelerating the entrance panel, Figures 3 - 4. Furthermore, the hydrostatic pressures generated in the water initiate bulging of the exit panel prior to perforation by the projectile, Figure 7.

Additional damage can occur to the exit panel after it has been perforated by the projectile and a complete analysis of a hydrodynamic ram event should include the response of the exit panel until it reaches equilibrium. Perforation of the exit panel for the analysis presented here can be readily performed. Predicting the steady state response of the exit panel in this analysis would not be cost effective. The exit panel would reach a steady state condtion in the millisecond regime while the integration time increment at 180 μs is 72 nanoseconds. It is clear that it would take an unreasonable amount of computing time to predict the steady-state response of the exit panel. However, Reference 9 describes a time increment criterion based on the rate of deformation which would permit the total number of integration cycles to be dependent on the total amount of deformation and not the wave transit time across the minimum altitude of the most deformed element as is the case with the present explicit scheme in EPIC-2. Incorporation of such a strain rate dependent time increment criterion would make predicting the steady-state response of the exit panel feasible.

Numerical simulation to assess the influence of projectile yaw and tumbling on the hydrodynamic ram effect would have to be carried out with the three-dimensional version of the EPIC code[10,11].

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[8] *Dr. P. Nietzel, private communication.*

[9] *Johnson, G. R., "Dynamic Analysis of Incompressible Viscous Fluids," Journal of Applied Mechanics, Vol 46, No 2, 1979.*

[10] *Johnson, G. R., "Further Development of the EPIC-3 Computer Program for Three-Dimensional Analysis of Intensive Impulsive Loading," AFATL-TR-78-81, July 1978.*

[11] *Johnson, G. R., "Further Development of EPIC-3 for Anisotropy, Sliding Surfaces Plotting and Materials Models," BRL Contractor Report to be published.*

APPENDIX A

VELOCITY VECTOR MAPS

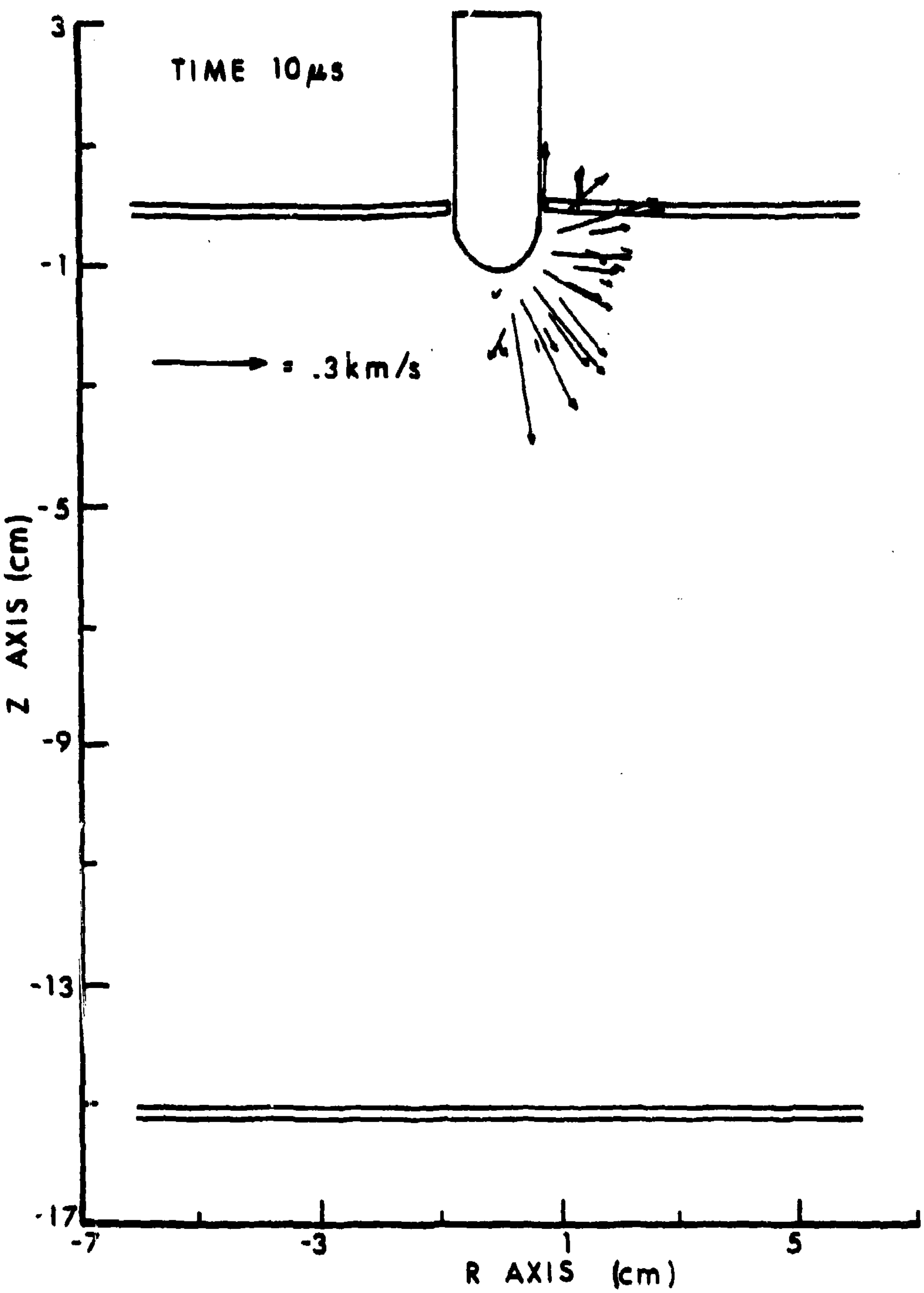

Figure A.1. Velocity vector map, t=10 μs

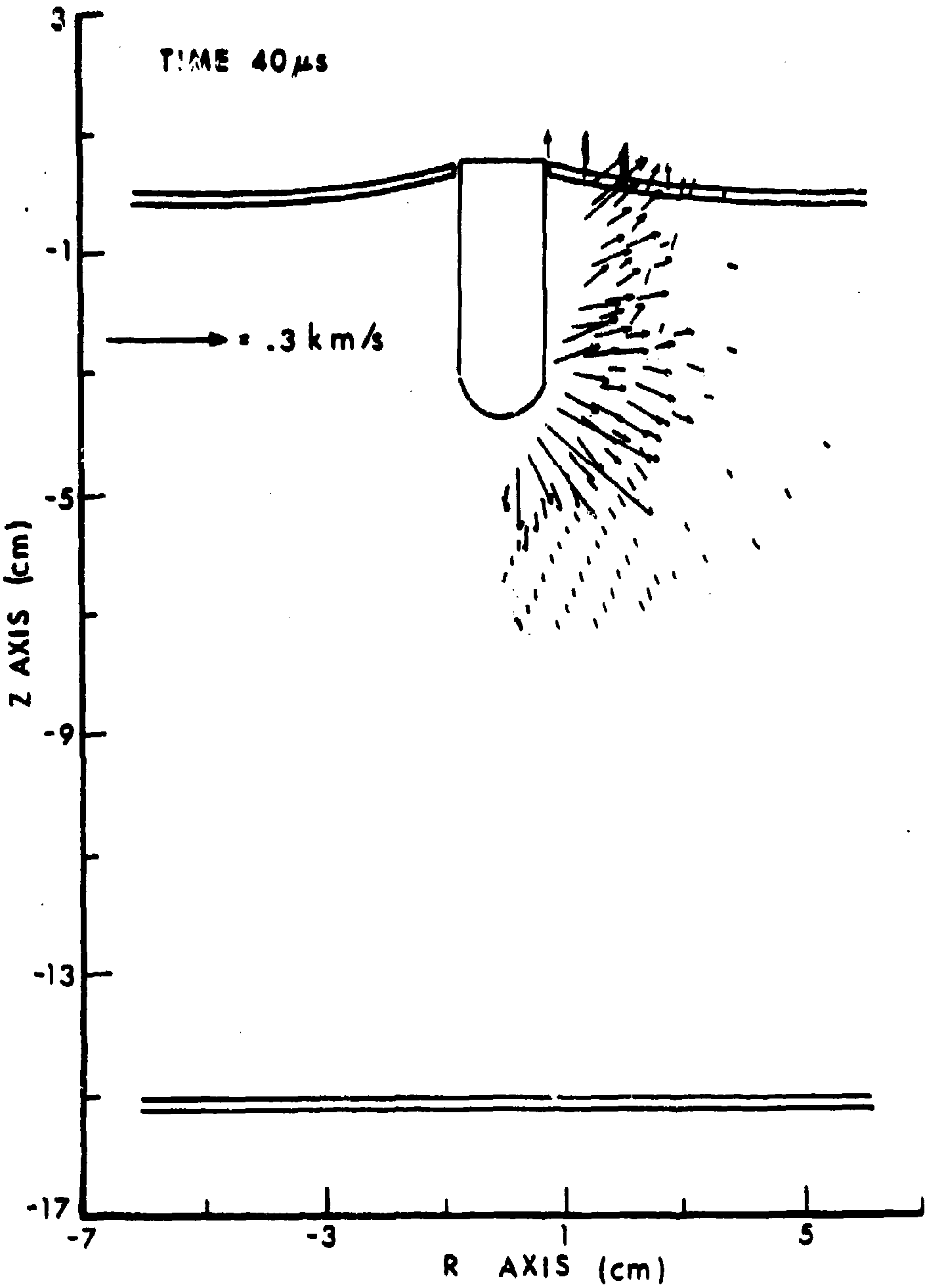

Figure A.2. Velocity vector map, t=40 μs

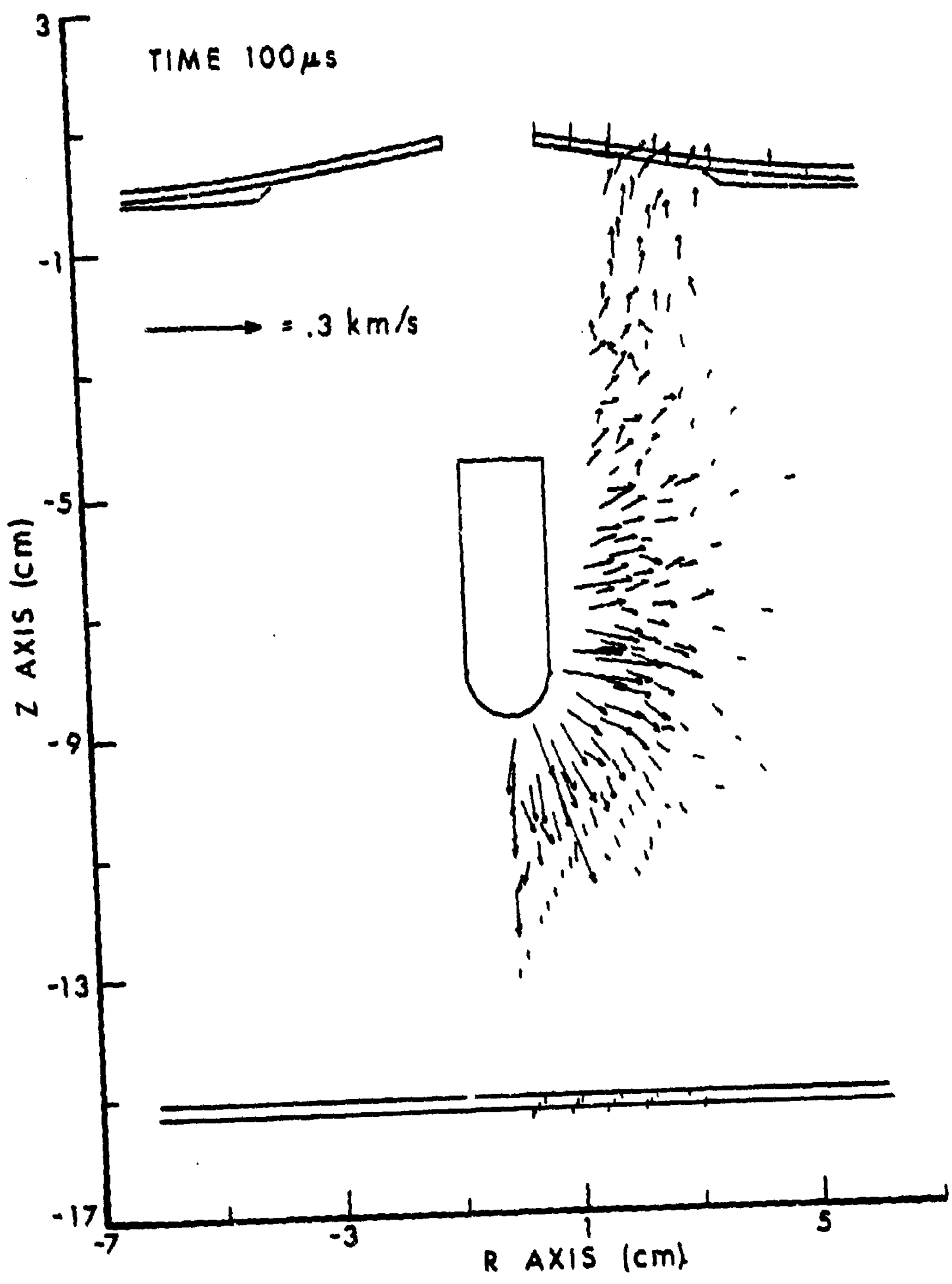

Figure A.3. Velocity vector map, t=100 μs

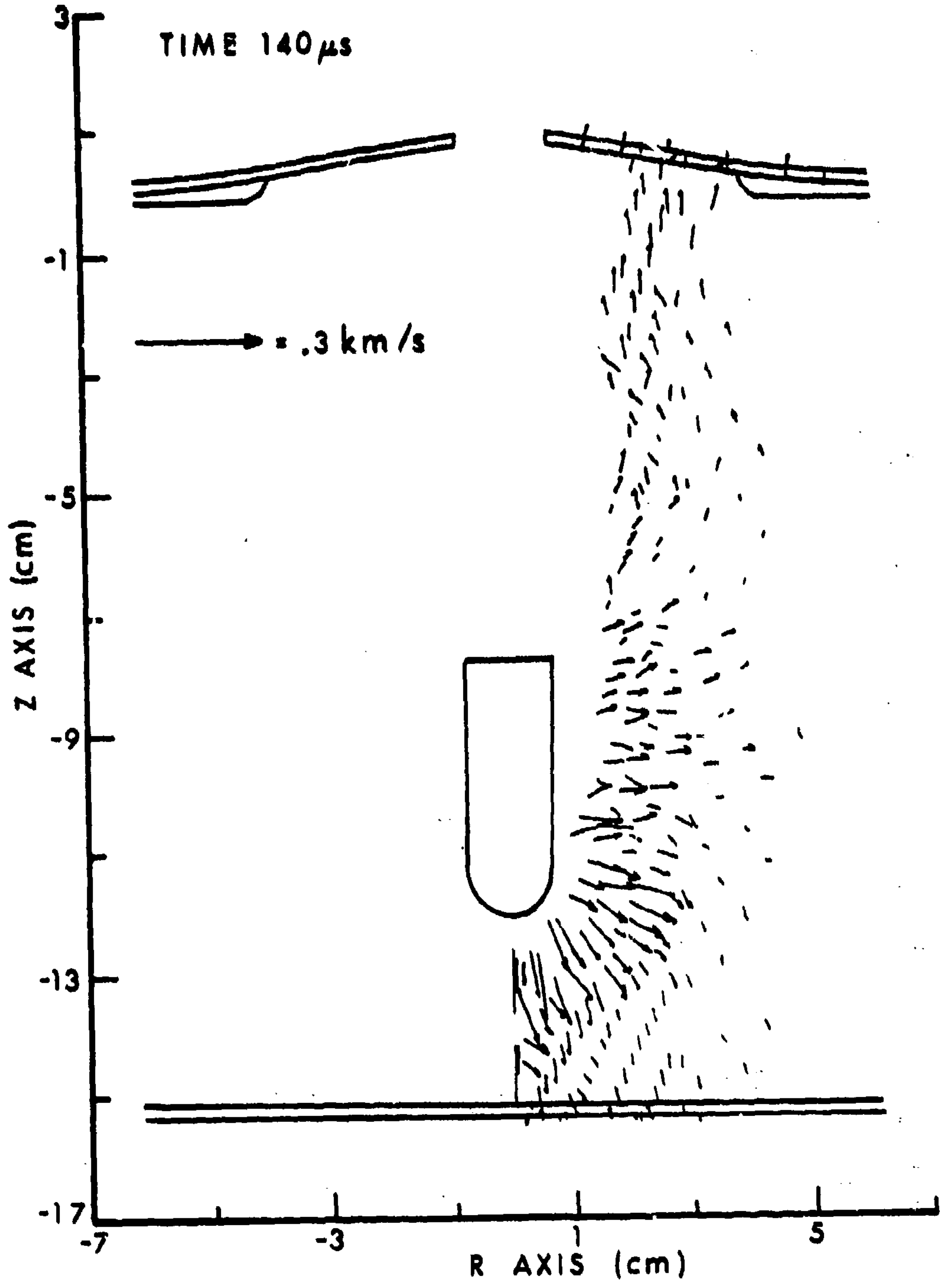

Figure A.4. Velocity vector map, t=140 μs

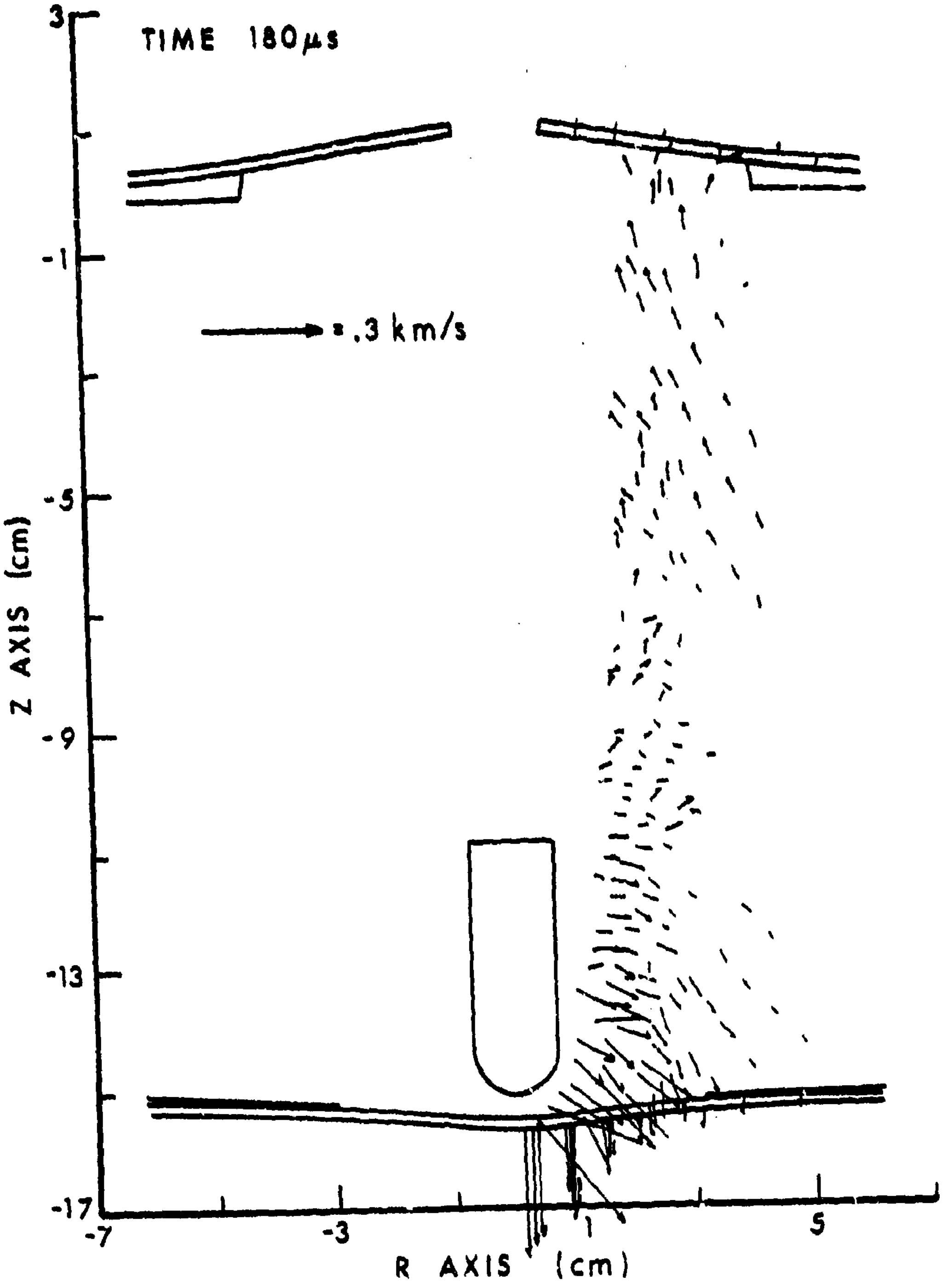

Figure A.5. Velocity vector map, t=180 μs

APPENDIX B

COMPUTATIONAL GRID MAPS

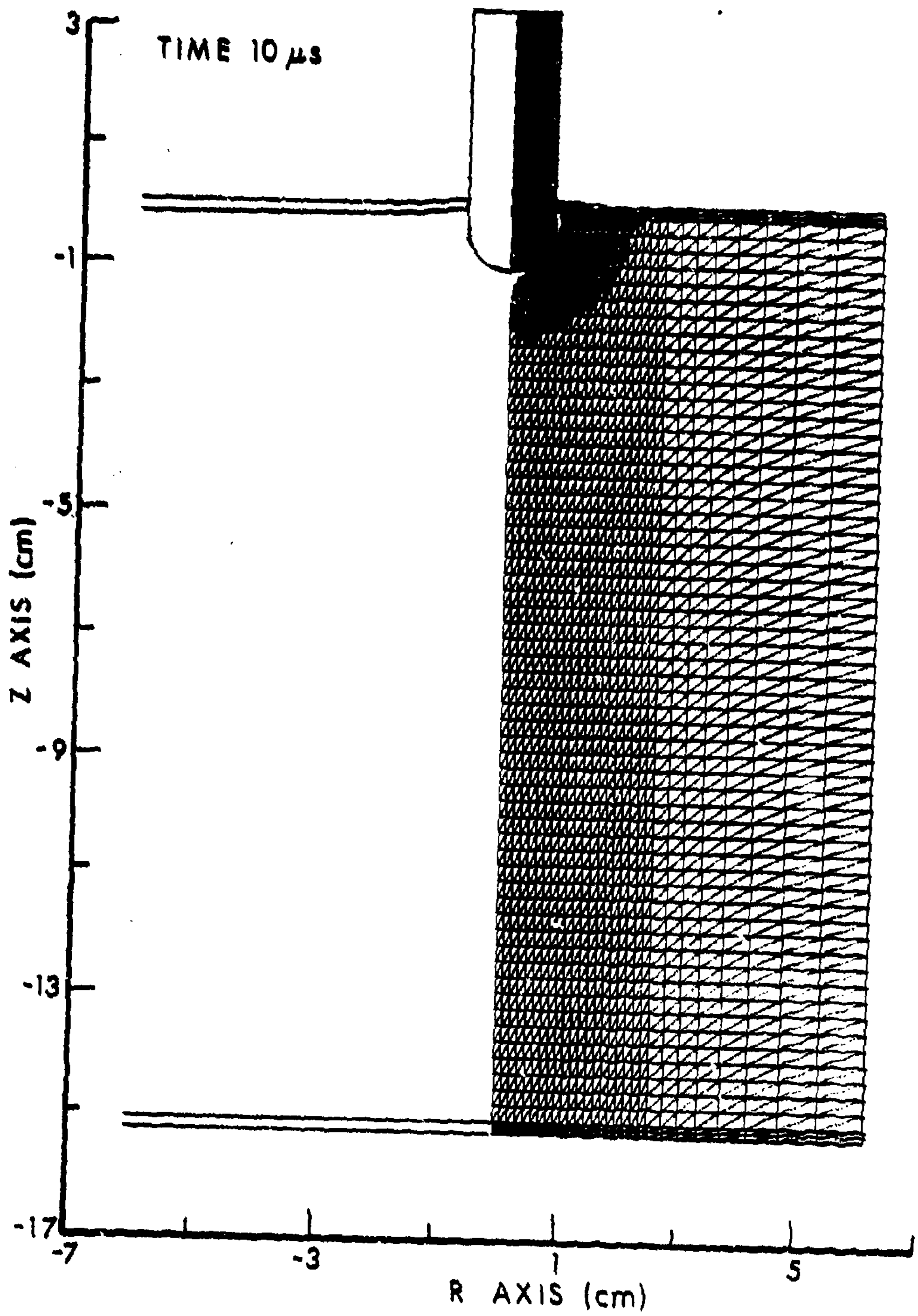

Figure B.1. Computational grid map, t=10 μs

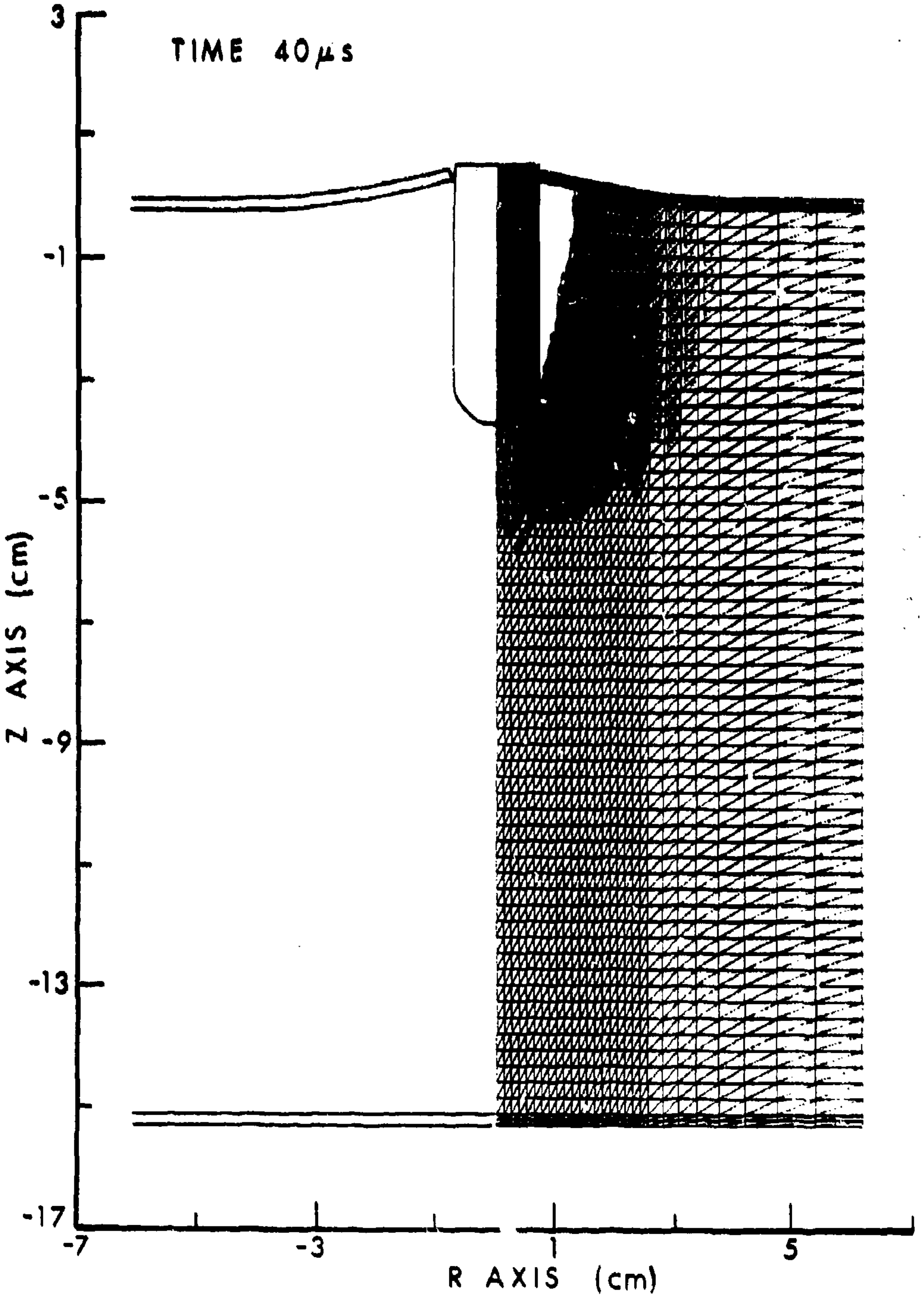

Figure 3.2. Computational grid map, t=40 μs

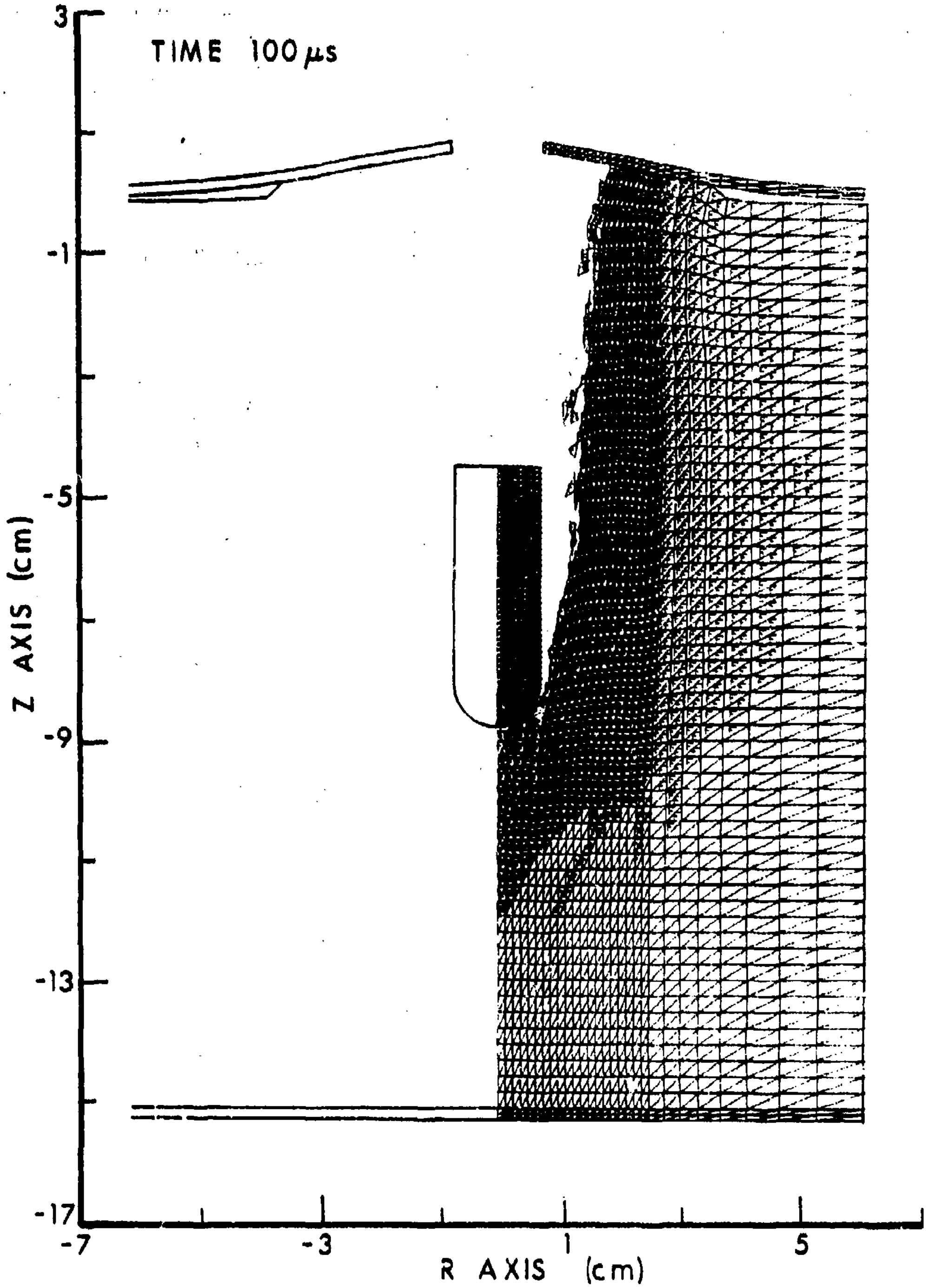

Figure B.3. Computational grid map, t=100 μs

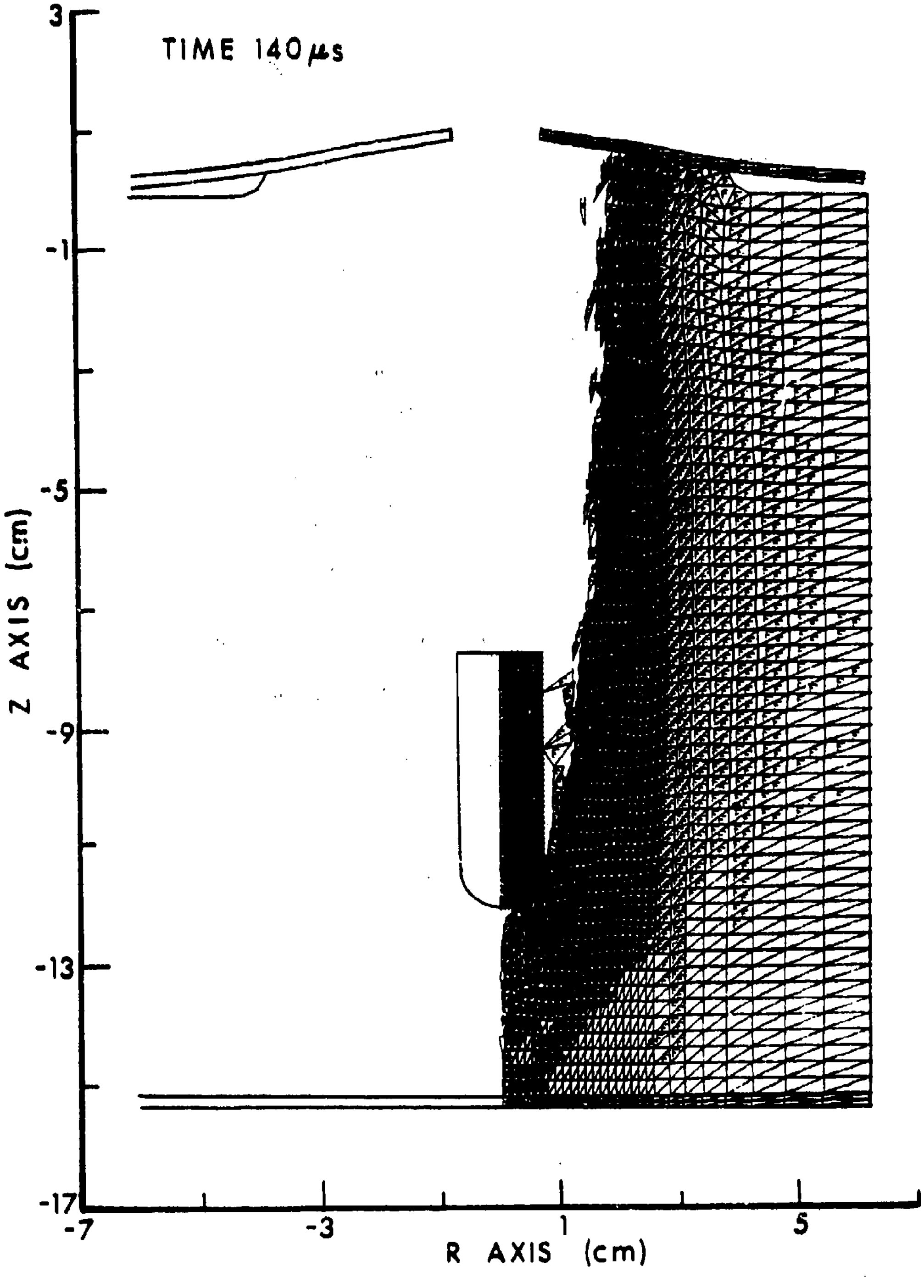

Figure B.4. Computational grid map, t=140 μs

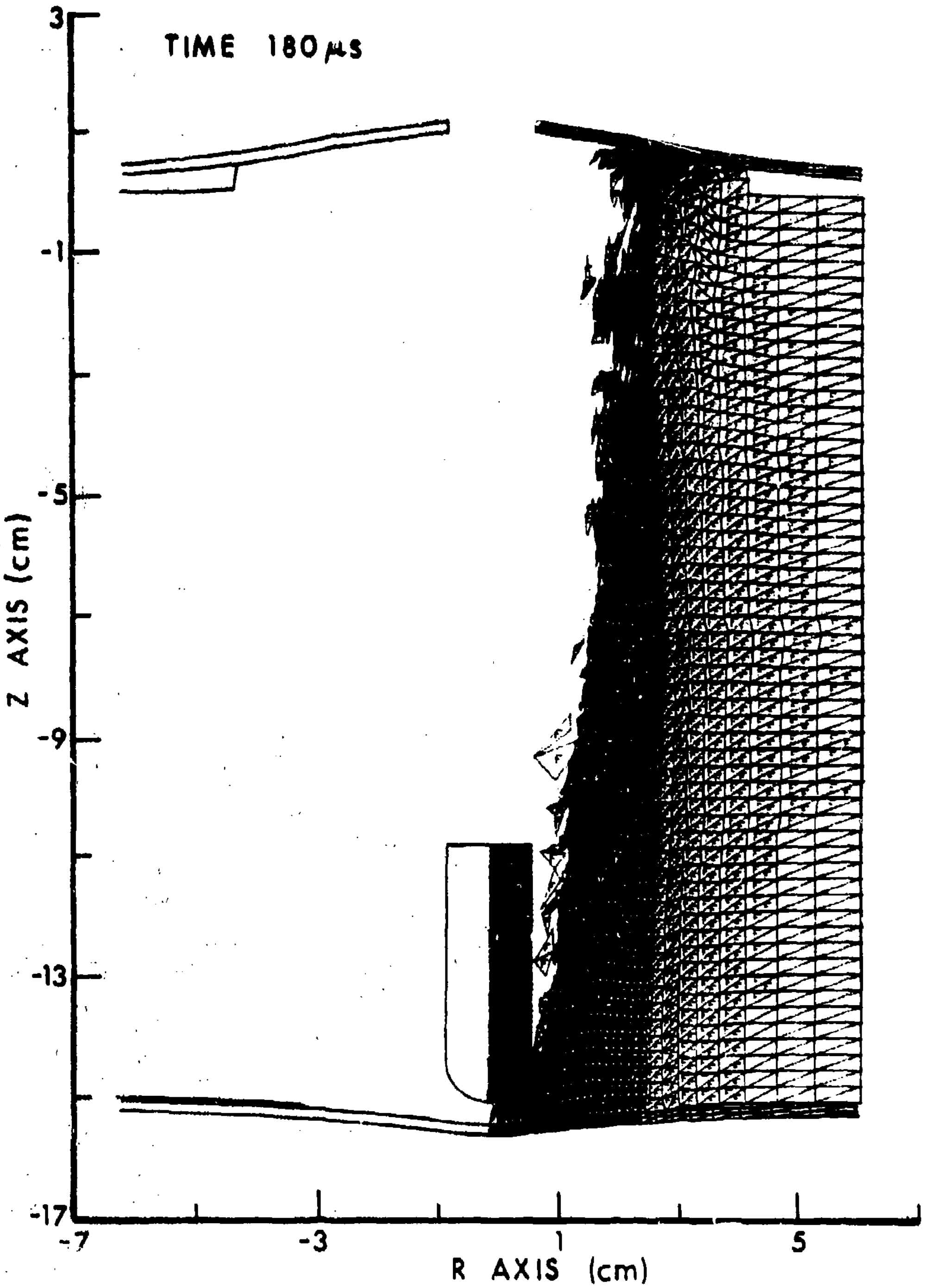

Figure B.5. Computational grid map, t=180 μs

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